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نموذج رقم (١٨)
اقرار والتزام بقوانين الجامعة الأردنية وأنظمتها وتعليماتها لطلبة الماجستير

أنا الطالب: محمد عبد المجيد محمد منصور الرقم الجامعي: ٨٠٨٠٧٦١
التخصص: هندسة ميكانيكية الكلية: الهندسة والتكنولوجيا

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EXERGY AND THERMAL PERFORMANCE ANALYSIS OF EVACUATED-TUBE VERSUS FLAT-PLATE SOLAR COLLECTOR

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This Thesis was Submitted in Partial Fulfillment of the Requirements for

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II

COMMITTEE DECISION

This Thesis/Dissertation (Exergy and thermal performance analysis of evacuated-tube versus flat-plate solar collector.) was successfully defended and approved on 11/12/2011

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Table of contents:

List of Figures:

List of Tables:

Nomenclature:

Notation	Description	Units
A_P	Plate area of flat-plate collector	m^2
C_p	Specific heat of water	kJ/kg K
$\dot{E}_d$	Destroyed exergy rate	kJ
$\dot{E}_{in}$	Inlet exergy rate	kJ
$\dot{E}_l$	Leakage exergy rate	kJ
$\dot{E}_{out}$	Outlet exergy rate	kJ
$\dot{E}_s$	Stored exergy rate	kJ
I	The incident solar energy	W
I_T	The incident solar energy per unit area	W/m^2
k	Thermal conductivity	W/m K
L	Plate length	m
$\dot{m}$	Volumetric flow rate of water	l/sec.
P_{in}	Inlet water pressure	bar
P_{out}	Outlet water pressure	bar
Q_u	Useful heat gain	W
T_a	Ambient temperature	K
T_{in}	Inlet water temperature	K
T_{out}	Outlet water temperature	K
T_P	Plate temperature	K
T_s	Apparent sun temperature	K
U_l	Overall loss coefficient	W/m^2 K
Greek Notations		
α	Absorptance of flat-plate collector	
ε	Emmitance	
η_{en}	Energy efficiency	
η_{ex}	Exergy efficiency	
η_d	Daily efficiency of the still	
θ	The angle of incidence	
τ	Transmittance	

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Abstract

In this work, flat-plate and evacuated-tube solar collectors were built and tested. The aim of this work is to study the thermal performance and exergy efficiency of the two collectors. The same water supplying tank is used, and all measuring tools, like thermocouples, data acquisition card, and pyranometer are used for both collectors, the readings also for both collectors are taken throughout ten days between 11:30AM and 12:30PM in the same time for each single day to achieve the results in the same environmental conditions, which helps us to create successful comparison between the two solar collectors.

It was found that the energy and exergy efficiency for evacuated-tube collector is better than that in flat-plate collector, but in the same time the amount of energy losses in evacuated-tube collector are more than that for flat-plate collector for high ambient temperatures and for hot water source.

Chapter One: Introduction

1.1 Study Importance

It is argued in the solar energy engineering community that as long as the energy obtained from the collector is large, it is immaterial to discuss second law efficiency since the energy incident on the collector is free. But the fact that the average evacuated tube collector temperature is higher than that of the flat plate, makes the losses higher and the second law efficiency lower. Also the mixing of hot and cold water that occurs at the user point is one of the known sources of irreversibility, which in turn reduces the second law efficiency.

In this work, a comparison will be made between the energy (first law) and exergy (second law) efficiency for flat-plate and evacuated- tube collectors. it will shed light on the actual value of energy obtained from both types of collectors, both theoretically and experimentally.

1.2 Study Objectives

Energy analysis are available for both types of solar collectors, but exergy analysis are available only for a special type of solar collectors, that is the serpentine one. No exergy analyses are available to date for local types of flat plate or for evacuated tube solar collectors.

This study aims at establishing a mathematical model for energy and exergy analysis of evacuated tube and locally-made flat plate solar collectors, along with building experimental rigs to validate both analyses.

Throughout the theoretical analysis and experimental findings of each type the efficiency and exergy relations can be found. Thus the performance of both systems can be compared.

1.3 Research methodology

An experimental setup is built and data recorded from instrument readings, then results are extracted from this data. A comparison is carried out to verify and judge the match of the two types of collectors, the evacuated-tube and the flat-plate.

During the experiment, the inlet and outlet temperatures of the water, incident solar radiation, ambient temperature, and the water flow rate were measured. The collected data is then plotted to give the relations between the water inlet temperature, ambient air temperature and incident solar radiation versus thermal efficiency, for evacuated-tube and flat-plate collector. After that, the calculations and results were generated for the exergetic efficiency for both collectors.

1.4 Thesis Layout

This thesis is composed of seven chapters among which this is the first.

Chapter Two covers a literature review for previous studies, in chronological order.

Chapter Three covers a theoretical analysis for energy and exergy for flat plate and evacuated tube solar collectors.

Chapter Four covers the thermal performance for flat-plate and evacuated-tube solar Collectors

Chapter 5 covers the experimental setup that containing the measurement devices. The specifications of each component were listed, and the combination of these devices was drawn in one figure.

Chapter 6 covers the results of the experimental work, starting from data listing for each solar collector to figures generating.

Chapter 7 covers discussion of experimental results for flat-plate and evacuated-tube solar collectors, and conclusion was extracted to show the best selection between them depending on the energy and exergy effiencies.

Chapter Two: Literature review

The energy and first law analysis for flat-plate and evacuated-tube collectors are available in the literature now for more than fourty years. Duffie and Beckman (2006) collected all theories concerning both types in the early version of their book in 1977. But the exergy analysis of those collectors was not included.

The expression Exergy was first coined by Slovenian Zoran Rant in a scientific meeting in 1953. He suggested that the term exergy should be used to denote "technical working capacity". The exergy theory was expanded in the 1970s' and the exponential growth of its applications were due to two very different but equally influential causes: one is the concise, clear and stimulating discussion offered by some textbooks of the 1960s' (Baehr, Schmidt, Obert, Hatsoupoulos and Keenan), that prompted generations of graduate students in Engineering Thermodynamics to enter the field; and the other is the so-called "oil crisis" of 1973, that forced governmental agencies and industries in industrial countries to concentrate on "energy savings" .

Xiaowu and Ben (2002), noted that earlier assessments of domestic-scale solar water heaters were based on the first law of thermodynamics. However, this kind of assessment cannot perfectly describe the performance of solar water heaters, since the essence of energy utilization is to extract available energy as much as possible. Therefore, it is necessary to evaluate domestic-scale solar water heaters based on the second law of thermodynamics. Exergy analysis was conducted with the aim of providing some methods to save cost, and keep the efficiency of domestic-scale solar water heater to the desired extent, At the same time figuring out related exergy losses.

It was shown that for an ordinary thermally insulated domestic-scale solar water heater, exergy losses due to imperfectly thermal insulation in collector and exergy losses due to imperfectly thermal insulation in storage barrel cannot be avoided. Exergy losses due to irreversibility in collector is mainly caused by irreversibility of heat transfer and exergy losses due to irreversibility in storage barrel is dominated by the mixing of water at different temperatures.

Luminosu, L. Fara (2002), suggested that it is common knowledge that the solar-thermal energy efficiency increases without extremum points with the flow rate, and similarly the fluid outlet temperature increases with the collecting area. The absence of maximum points for the functions of energy efficiency as function of mass flow has created difficulties in the design of flat-plate solar collectors. The exergy efficiency of a flat-plate solar collector, which is a function of mass flow and collector area, presents points of local maxima and a point of global maximum.

Farahat et al (2007) developed an exergetic optimization of flat plate solar collectors to determine the optimal performance and design parameters of these solar to thermal energy conversion systems. A detailed energy and exergy analysis is carried out for evaluating the thermal and optical performance. Exergy flows and losses as well as exergetic efficiency were obtained for a typical flat-plate solar collector under given operating conditions. In this analysis, the following geometric and operating parameters were considered as variables: the absorber plate area, dimensions of solar collector, pipes' diameter, mass flow rate, fluid inlet, outlet temperature, the overall loss coefficient, etc. A simulation program was developed for the thermal and exergetic calculations. The results of this computational program are in good agreement with the experimental measurements noted in the previous literature. Finally, the exergetic optimization has been carried out under given design and

operating conditions and the optimum values of the mass flow rate, the absorber plate area and the maximum exergy efficiency have been found. The incremented quantities are the absorber plate area from 1 to 10 m^2 and the mass flow rate of fluid from 0.001 to 0.009 kg/s. The calculated values for the global maximum point are plate area 9.14 m^2, mass flow rate 0.0087 kg/s, exergy was 3.898%.

Budihardjo, Morrison (2008) carried out a comparison between water-in-glass evacuated tube solar water heaters and flat-plate systems operating in Sydney. He showed that an evacuated tube system with 30 tubes has slightly lower energy savings than a two panel (3.7m^2) flat plate system. The performance of evacuated tube collector system was shown to be less sensitive to tank size than flat plate collector systems.

Jianfeng et al (2010) analyzed and optimized associated heat transfer and exergetic performances of solar receiver pipe with solar selective coating. Because of the heat losses of natural convection and infrared radiation, the energy absorption efficiency had a maximum at optimal incident energy flux. As the pipe radius decreased or flow velocity increased, the wall temperature dropped for higher heat transfer coefficient, while the heat absorption efficiency increased. Along the flow direction, the heat absorption efficiency almost linearly decreased, while the exergetic efficiency increased and then decreased. As the inlet temperature increased, the heat absorption efficiency of the solar receiver pipe decreased, while the exergetic efficiency of absorbed energy obviously increased, so the exergetic efficiency of incident energy reached maximum at the optimal inlet temperature.

Liangdong et al (2010), investigated the thermal performance of the individual glass evacuated tube solar collector by analytical method. The solar collector considered in

this study was a two-layered glass evacuated tube, and the absorber film was deposited in the outer surface of the absorber tube. The heat loss coefficient and heat efficiency factor were analyzed using one-dimensional analytical solution. and the influence of air layer between the absorber tube and the copper fin on the heat efficiency was also studied. The results showed that the functional relationship between the heat loss coefficient of the glass evacuated tube solar collector and the temperature difference between the absorbing coating surface and the ambient air was nonlinear. In the different ambient temperature, the heat loss coefficient of the solar collector should be calculated by different expressions. The results showed that the radiation heat transfer coefficient increased with increase of the ambient temperature for the same difference between the absorbing coating and the ambient temperatures. And, for the same ambient temperature, the radiation heat transfer coefficient increases with increase of temperature difference. Therefore, the relation between the ambient temperature and the temperature difference is non linear. The radiation heat transfer coefficient is larger compared with the heat transfer coefficient due to conduction. They found that the temperature difference increases nonlinearly with increase of temperature difference, especially for the larger ambient temperature. And it also increases when the ambient temperature increases if the temperature difference is given, indicating that the thermal loss increases with increase of the absorber tube owing to the larger radiation heat transfer coefficient.

The above literature review shows that no exergy analysis was made for evacuated tube collectors, nor for local types of flat plate collectors. This distinguishes this work from previous ones. Moreover, the previous study of Farahat et al (2007) considered very low values of mass flow rate, which does not conform to ASHRAE Standard 93-86 which specifies a flow rate of 0.02 kg/s per m^2 of collector area.

Chapter Three: Theoretical Analysis For Energy And Exergy for Flat-Plate and Evacuated-Tube Solar Collectors

3.1 Basic description of flat-plate Solar Collectors

The layout of a typical flat-plate solar collector is shown in Figure 3.1 where the flow of cold water is from the lower side, and the flow of the hot water from the upper one. Under and between the pipes there is a black surface coated with a selective coating that absorbs nearly all incident solar radiation (absorbing plate). Under this black surface there is an insulation layer, this layer helps to prevent heat dissipation from the bottom of the collector.



Figure 3.1 Flat-plate solar collector.

Water flows through the pipe to gain the heat that is collected by the absorbing plate due to incident solar radiation.

3.2 Basic description of evacuated-tube Solar Collectors

The principle of heat collection in evacuated tube solar collector depends on selective coating that allows the solar radiation to enter the evacuated pipe and prevents it to reflect out of the pipe. The evacuated space between the outer tube and inner tube cancels the negative factors of convection and conduction between the pipe surface and the environment as shown in Figure 3.2 [Ecotasmania, 2011].

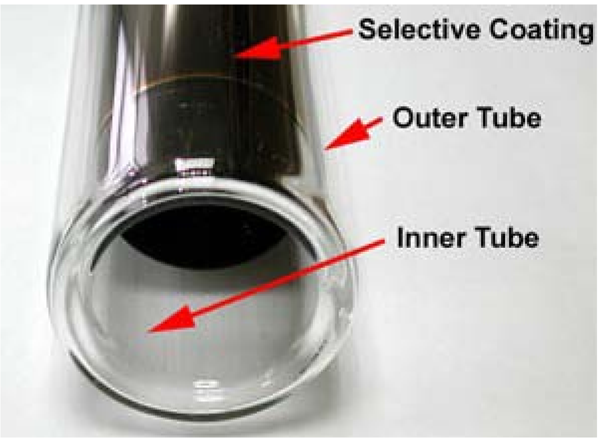


Figure 3.2 Evacuated-tube collector [Ecotasmania].

The energetic analysis gives the amount of solar energy that is converted to heat supplied to water. It is not enough to determine the useful energy produced by the end user. The exergy analysis is important to give an idea about the quality of this energy.

Exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference

environment. from this definition, exergy became a tool used to judge the activity of operating a machine or a system, or replace it with another, depending on its output useful energy.

3.3 General form of Exergy Balance Equation

To determine exergy one has to show the general form of exergy balance equation, Farahat et al (2007),

$$\dot{E}_{in} + \dot{E}_s + \dot{E}_{out} + \dot{E}_l + \dot{E}_d = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where $\dot{E}_{in}$, $\dot{E}_s$, $\dot{E}_{out}$, $\dot{E}_l$ and $\dot{E}_d$ are inlet, stored, outlet, leakage, and destroyed exergy rate, respectively.

3.3.1 Inlet Exergy Rate Equation

The inlet exergy rate with fluid flow and the absorbed solar radiation exergy rate are the two quantities that form total inlet exergy rate. The inlet exergy rate with fluid flow is given by (Farahat et al (2007)):

$$\dot{E}_{in,f} = \dot{m}C_p\left(T_{in} - T_a - T_a \ln\left(\frac{T_{in}}{T_a}\right)\right) + \frac{\dot{m} \vartriangle P_{in}}{\rho} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

$\dot{m}$ is The mass flow rate of fluid, T_{in} is the inlet fluid temperature, T_a is the ambient temperature, P_{in} is inlet fluid pressure, ρ is the fluid density.

Considering the sun as an infinite thermal source, the absorbed solar radiation exergy rate equation is

$$\dot{E}_{in,Q} = \eta_o I_T A_P\left(1 - \frac{T_a}{T_s}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

Where η_o and T_s are the optical efficiency and apparent sun temperature which equals 75% of blackbody temperature of the sun.

3.3.2 Stored Exergy Rate Equation

The stored exergy rate equals to zero in this work because of steady state condition. And to avoid any heat accomulation in the evacuated-tube collector manifold the outlet water pipe of the flat- plate collector is positioned in the same level of the outlet water pipe of the evacuated-tube collector.

3.3.3 Outlet Exergy Rate Equation

The third term in the general exergy balance equation is the outlet exergy rate for the fluid flow and is given as (Farahat et al (2007)):

$$\dot{E}_{out,f} = -\dot{m}C_p\left(T_{out} - T_a - T_a \ln\left(\frac{T_{out}}{T_a}\right)\right) - \frac{\dot{m} \bigtriangleup P_{out}}{\rho} \ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

3.3.4 Leakage Exergy Rate Equation

The development of solar collector performance depends on minimizing the fourth and fifth terms of the general exergy balance equation, the fourth term is the leakage exergy rate, the leakage rate is in heat that flows from the absorber plate to the environment, (Farahat et al (2007)):

$$\dot{E}_l = -U_l A_P (T_P - T_a)\left(1 - \frac{T_a}{T_P}\right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.5)$$

Where U_l is the overall loss coefficient, and T_P is the plate temperature.

3.3.5 Destroyed Exergy Rate Equation

The last term in the general form of exergy balance equation determines the destroyed exergy rate that is produced from three sources; the first source is the temperature difference between the absorber plate surface and the sun, this source is calculated by the equation(Farahat et al (2007)):

$$\dot{E}_{d,\Delta T_s} = -\eta_o I_T A_P T_a \left(\frac{1}{T_p} - \frac{1}{T_s}\right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. (3.6a)$$

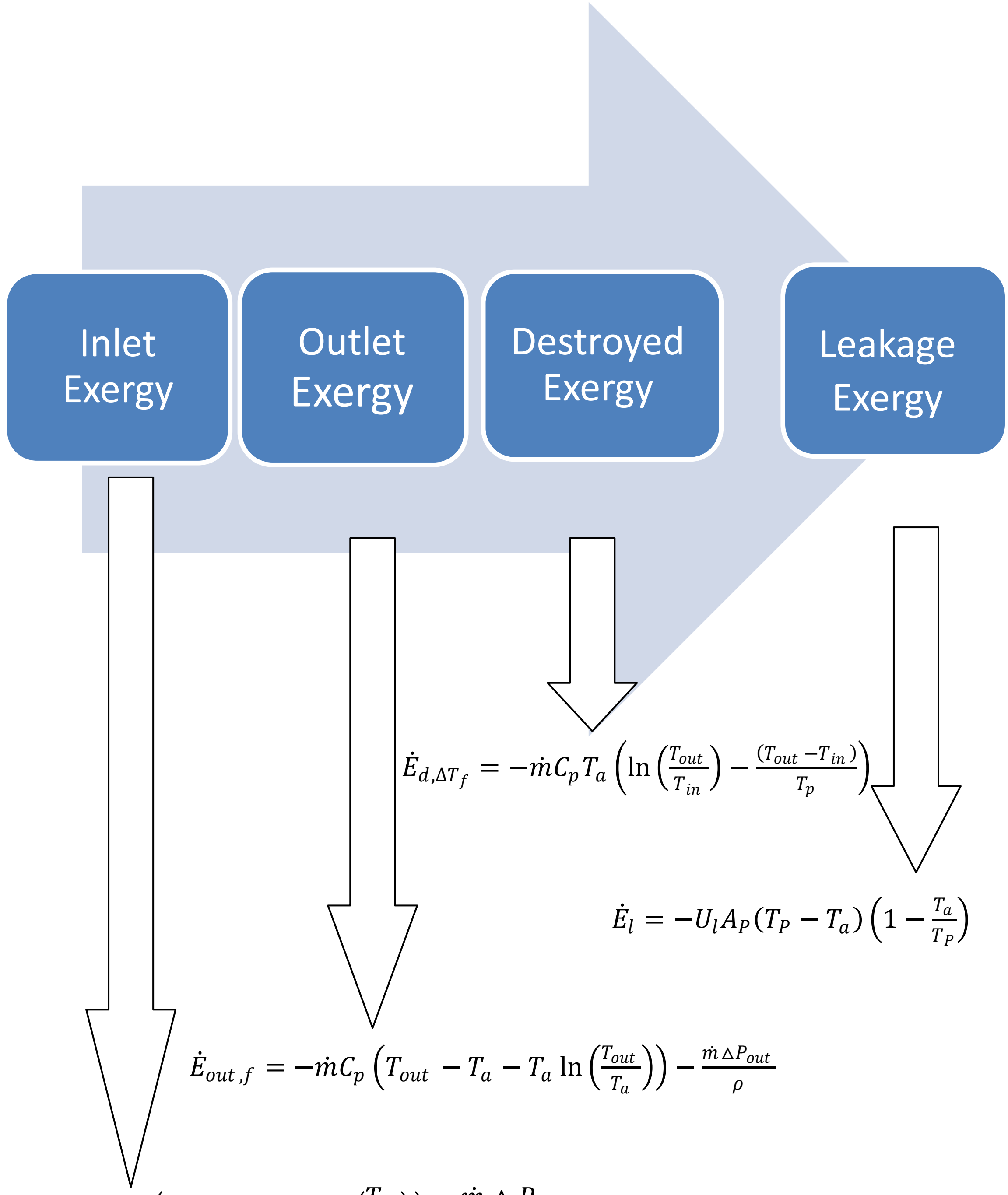
Equation 3.6b shows the second source, which is the pressure drop.

$$\dot{E}_{d,\Delta P} = -\frac{\dot{m}\Delta P}{\rho} \frac{T_a \ln\left(\frac{T_{out}}{T_a}\right)}{(T_{out} - T_{in})} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.6b)$$

The third source is the temperature difference between the absorber plate surface and the working fluid, as shown in equation 3.6c.

$$\dot{E}_{d,\Delta T_f} = -\dot{m} C_p T_a \left(\ln\left(\frac{T_{out}}{T_{in}}\right) - \frac{(T_{out} - T_{in})}{T_p}\right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (3.6c)$$

An illustration of the relation between equations 3.2, 3.5, and 3.6c is shown in a Sankey-type diagram Fig. 3.3



$$\dot{E}_{d,\Delta T_f} = -\dot{m}C_p T_a \left(\ln\left(\frac{T_{out}}{T_{in}}\right) - \frac{(T_{out} - T_{in})}{T_p}\right)$$

$$\dot{E}_l = -U_l A_P (T_P - T_a)\left(1 - \frac{T_a}{T_P}\right)$$

$$\dot{E}_{out,f} = -\dot{m}C_p \left(T_{out} - T_a - T_a \ln\left(\frac{T_{out}}{T_a}\right)\right) - \frac{\dot{m}\,\Delta P_{out}}{\rho}$$

$$\dot{E}_{in,f} = \dot{m}C_p \left(T_{in} - T_a - T_a \ln\left(\frac{T_{in}}{T_a}\right)\right) + \frac{\dot{m}\,\Delta P_{in}}{\rho}$$

Fig. 3.3 Exergy flow chart

3.4 Exergy Efficiency

The exergy efficiency is the main factor of evaluating solar collector, because exergy efficiency determines the increase of fluid flow exergy upon the primary radiation exergy by the radiation source.

Analyzing the general form of exergy balance and comparing all terms of it with the energy input (solar radiation), gives us the exergy efficiency, as shown in equation 3.7 (Farahat (2007)):

$$\eta_{ex} = \frac{\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right) - \frac{\Delta P}{\rho}\right]}{I_T A_p\left(1 - \frac{T_a}{T_s}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3.7)$$

Where η_{ex} is the exergy efficiency. According to the application and type of the solar collector one or more terms may be cancelled from the general form of exergy balance equation. In this work and in both solar collectors the term of pressure is cancelled because there is no pump used and the pressure in the outlet and inlet is atmospheric pressure. This means that the exergy efficiency becomes as shown in equation 3.8 (Farahat (2007):

$$\eta_{ex} = \frac{\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I_T A_p\left(1 - \frac{T_a}{T_s}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3.8)$$

Chapter Four: Thermal Performance for Flat-Plate and Evacuated-Tube Solar Collectors

Starting from the objectives stipulated for any solar collector, which are to achieve temperature difference between the inlet water flows and the outlet water, the efficiency of converting the solar energy to heat supplied to the water may be calculated.

4.1 The Thermal Performance for Flat-Plate Solar Collector

The basic construction of the flat-plate solar collector used in this work consists of the frame that housing the pipes, black surface, and insulating layer. Other parts like glass cover considered as accessories that are used depends on the application of the flat plate solar collector.

The type of fluid passing through the pipes of flat plate solar collector, the style of pipes distribution, and the cover of the flat-plate solar collector, are the parameters of classification of flat plate solar collectors. In this thesis water, parallel tubes, and glassed flat-plate solar collector is used as shown in Figure 4.1, [the encyclopedia of alternative energy and sustainable living] and Table 4.1 shows the specifications of the flat-plate solar collector used in this study.

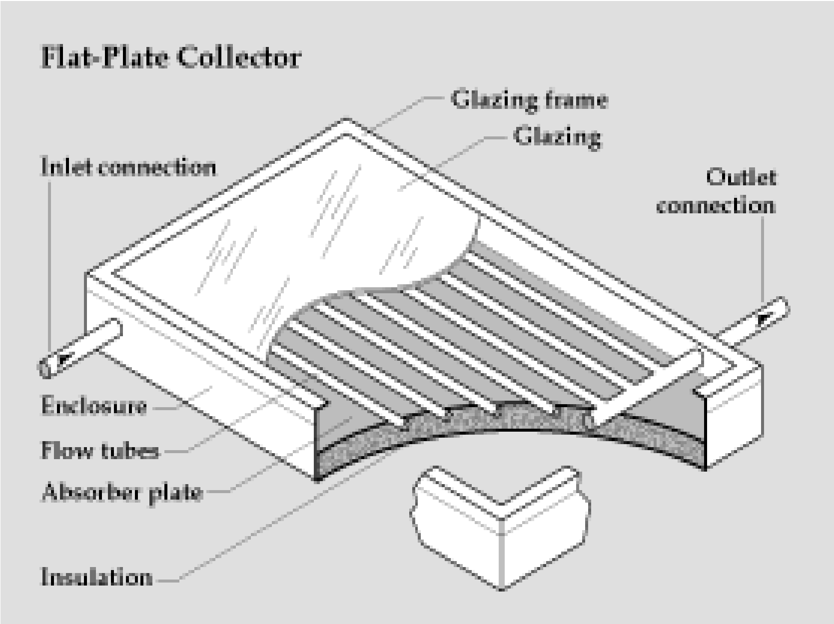


Figure 4.1 Flat-plate solar collector [the encyclopedia of alternative energy and sustainable living]

Table 4.1 Flat-plate collector specifications

Parameter	Units	Value
A_p	m^2	1.34
D	mm	15
W	mm	100
δ	W/m°C	0.7
τ		0.902
α		0.962
Glazing thickness	mm	4

The following is the analysis summarized by Duffie and Beckman (2006), two terms are used to calculate the energetic efficiency, the first term is the useful heat gain to the water, which is:

$$Q_u = \dot{m}C_p(T_{out} - T_{in}) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4.1)$$

Where $\dot{m}$, C_p, T_{out} and T_{in}, are the water mass flow rate, heat capacity, and fluid inlet, outlet temperature, respectively. The water mass flow rate can be measured and controlled. The inlet and outlet water temperature are measured using thermocouples.

The second term that must be compared with the amount of heat gain is the amount of incident solar energy on the area of the collector plate. This term is usually measured by a pyranometer.

Thus the basic energetic efficiency equation is:

$$\eta_{en} = \frac{Q_u}{I_T A_p} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4.2)$$

Where η_{en}, I_T and A_p are the energetic efficiency, incident solar energy per unit area of the absorber plate, and the area of the absorber plate, respectively.

Substituting equation (1) into equation (2) we can find out the energetic efficiency by the following equation.

$$\eta_{en} = \frac{\dot{m}C_p(T_{out} - T_{in})}{I_T A_p} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4.3)$$

To create a diagram for flat plate energetic efficiency we have to measure the inlet and outlet water temperature, and the incident solar radiation, for each water flow rate, plate area, and incident angle.

4.2 The Thermal Performance for Evacuated-Tube Solar Collector

The evacuated-tube collector used in this work was of the simple type, where the water is directly heated by solar energy, Selective coated glass allows the solar radiation to enter the core of the tube and prevents it to go out of the tube, this makes the solar energy to be converted to heat gain and supplied to water throughout the length of the tube.

Inlet and outlet position of the fluid through the tube, and the shape of the tube, are the parameters of classification of evacuated tube solar collector. In this thesis one inlet and outlet position fluid flow (water enters and exits the tube from the same place), straight shape evacuated tube is used as shown in Figure 4.2.



Figure 4.2 Evacuated-tube solar collector.

The same equations used for flat plate collector are used to calculate the heat gain and the energetic efficiency for evacuated tube collector considering the difference in the area and the outlet water temperature.

Chapter Five: Experimental setup

The experiment setup consists of two rigs, as shown in Figures 5.1 and 5.2.

Each system is composed of its own collector, tank, piping, and thermocouples. Both systems share a pyranometer and a data acquisition card.

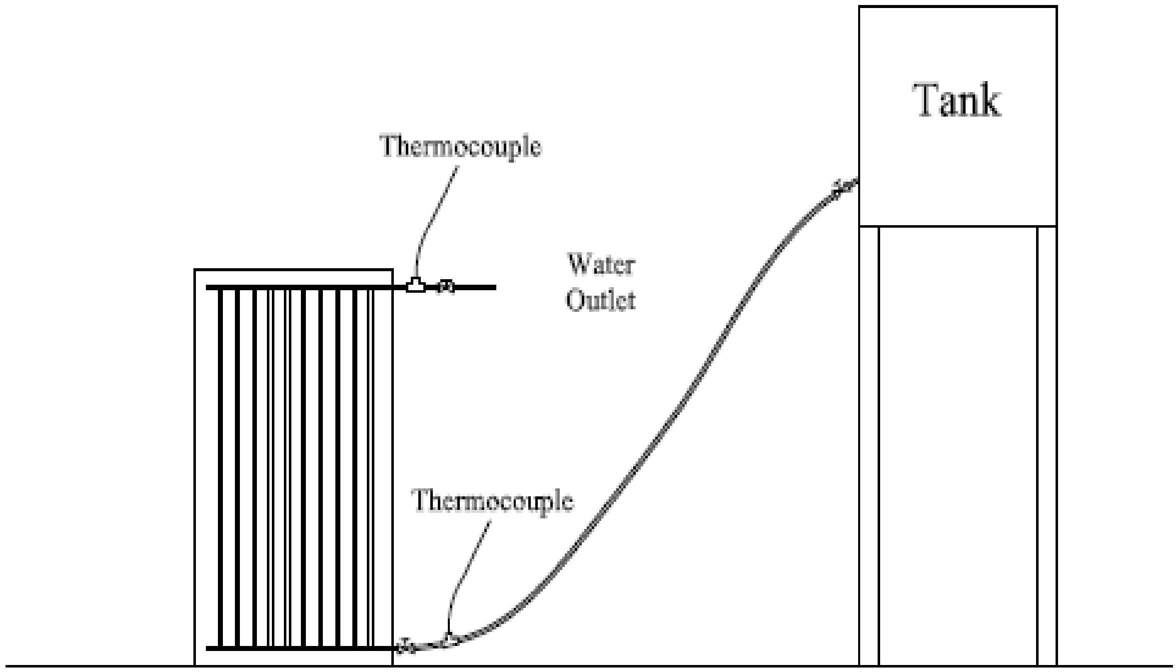


Figure 5.1 Flat-plate solar collector rig

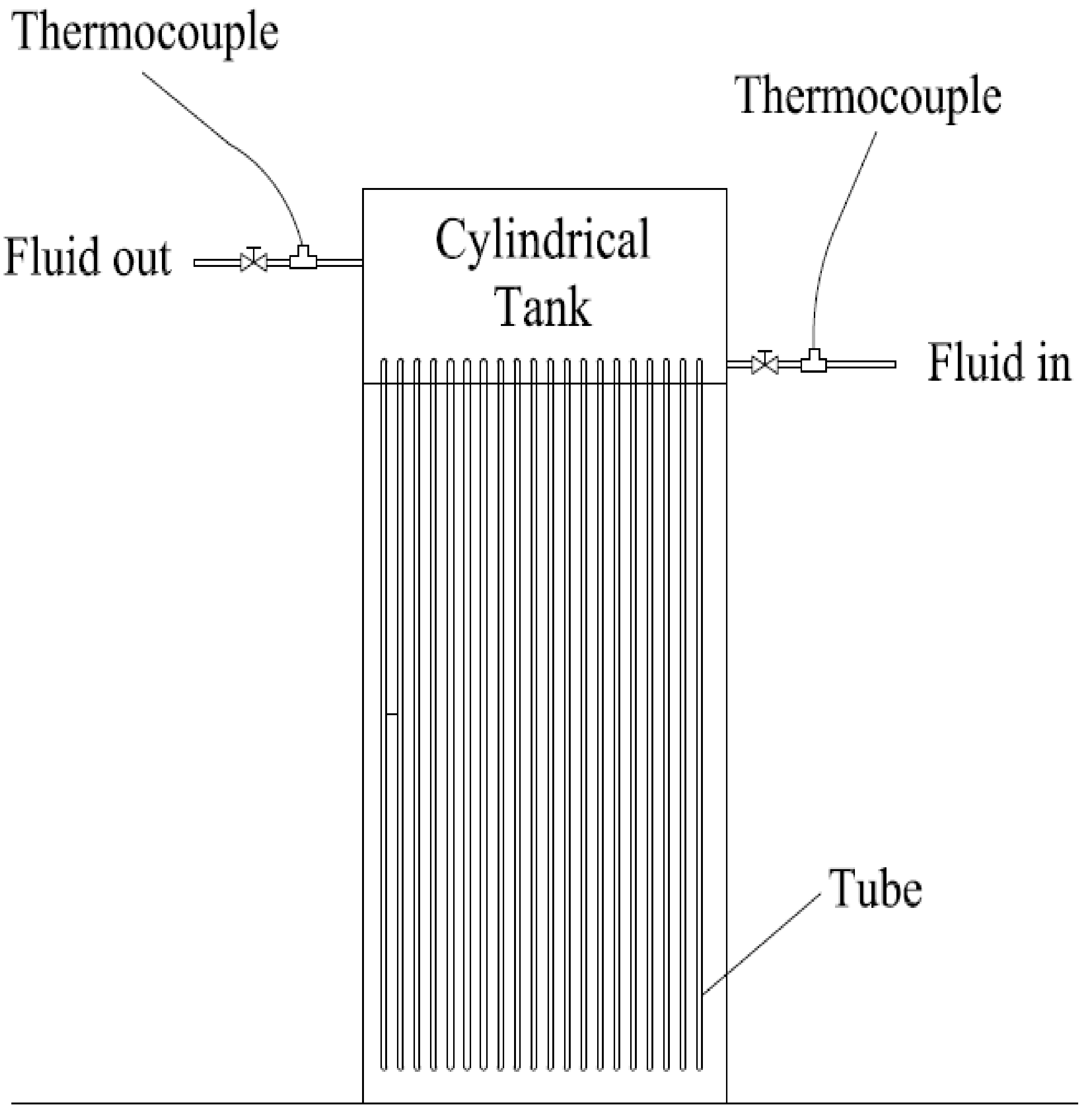


Figure 5.2 Evacuated-tube solar collector rig.

5.1 The System description

Both flat-plate and evacuated-tube collectors share the same water-supplying tank. The level of supply tank is two meters above the ground, one pipe supplies water for two collectors to ensure that water enters the two collectors at the same temperature. Thermocouples were put in the inlet water pipe, outlet water pipes for two collectors measuring the temperature in each position mentioned, converted to an electrical signal by the data acquisition card, and saved by the computer into excel sheet.

5.2 Thermocouples

The thermocouples used in this experiment are K-type, the range of temperature measured in this type is -200 ℃ to 1250 ℃, and the percentage error equals 0.75% for temperature above 0℃. The materials of poles is K-type, and the relation between the output millivolts and the temperature measured are shown in Table A.1

of Appendix A.

5.3 Data acquisition card

The output millivolts of the thermocouples are meaningless without translating it into considered standard value of temperature, this operation is performed by the Data Acquisition Card. Besides, the card is able to treat more than one thermocouple output in the same time. The type of data acquisition card used in this experiment is high-precision DAQ- NI USB-9211Al. It is four channels of twenty four bit thermocouple input, plug and play connectivity via USB, the card is compatible with J, K, R, S, T, N, E, and B thermocouples types, its dimensions are 12.1 by 8.6 by 2.5 cm and it includes NI-DAQmx driver software and LabVIEW signal express LE for Windows.

Figure 5.3 shows the Data Acquisition Card, and Appendix B shows a Table of its Specifications.



Figure 5.3 Data Acquisition Card.

5.4 Solar radiation measurements

The solar radiation measurement devices used in this experiment consists of two components, the first is the Kip and Zonen pyranometer, CM11, which is a collection of the thermopiles, black carbon disc. The second component is the Kip and Zonen Solar Integrator. It transforms the output signal of the pyranometer and integrates it into a digital display.

The following is the specifications of the pyranometer.

- Response time 95%: 18 seconds.
- Zero offset due to 200 W/m^2: < 15W/m^2.
- Non-stability (% change per year): < ±1%.
- Non linearity (0 to 1000 W/m^2): < ±2.5%.

- Directional error (at 80° with 1000 W/m^2 beam): < ±20 W/m^2.

5.5 Experimental Procedure

To have as much as accurate results, the readings must consider the following Stipulations, as per ASHRAE 93-86 Standard:

• Full sunny day (especially in the reading time).

• The level of solar radiation is more than 700W/m^2.

• The flow rate of water is 0.02kg/m^2.s.

• Wind speed is less than 3m /s

• In each day, five readings are taken to have one average result.

If all of the previous stipulations are achieved, the system for each solar collector can be run in the same time to record the output signals of inlet and outlet water temperatures, and ambient air temperature.

Each system is run at least 1 hour before solar noon to reach steady state. The first temperature and radiation measurements is taken 30 minutes before solar noon, the second at 15 minutes and the third at solar noon. Similar measurements are taken at 12:15 and 12:30 PM.

Chapter Six: Results

6.1 Flat-plate solar collector tables and curves

Figure 6.1 shows the variation of the flat-plate collector efficiency with ΔT/I.

Appendix C shows the table of results for flat-plate solar collector, which the above curve was created from it.

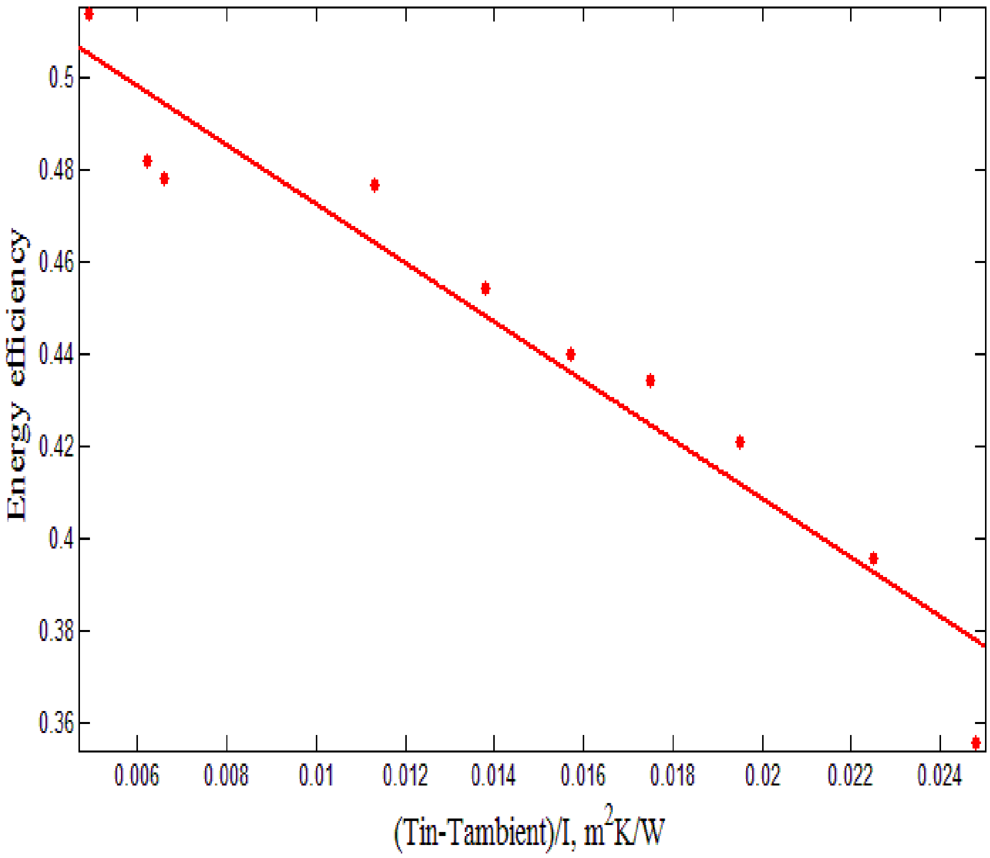


Figure 6.1 Energy efficiency for flat-plate collector (15/10-11/11)/2011

Fig. 6.2 shows the variation of the flat-plate collector efficiency with the inlet temperature.

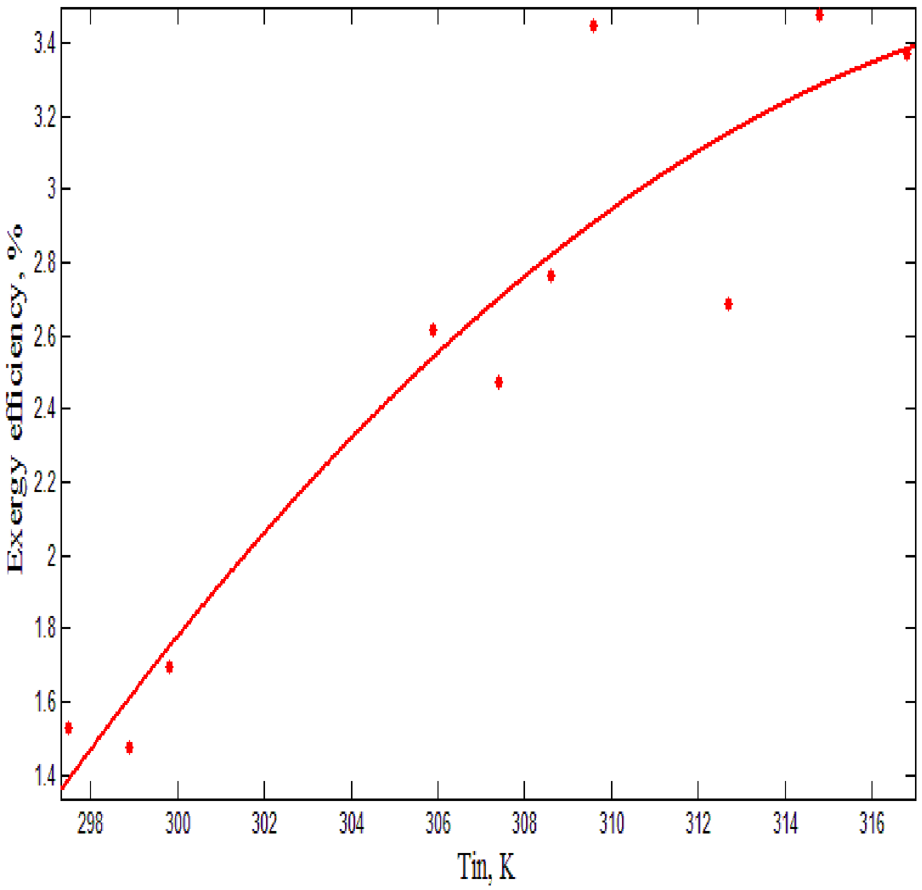


Figure 6.2 Exergy efficiency vs. inlet temperature for flat-plate collector

Fig. 6.3 shows the variation of the flat-plate collector exergy efficiency with the energy efficiency.

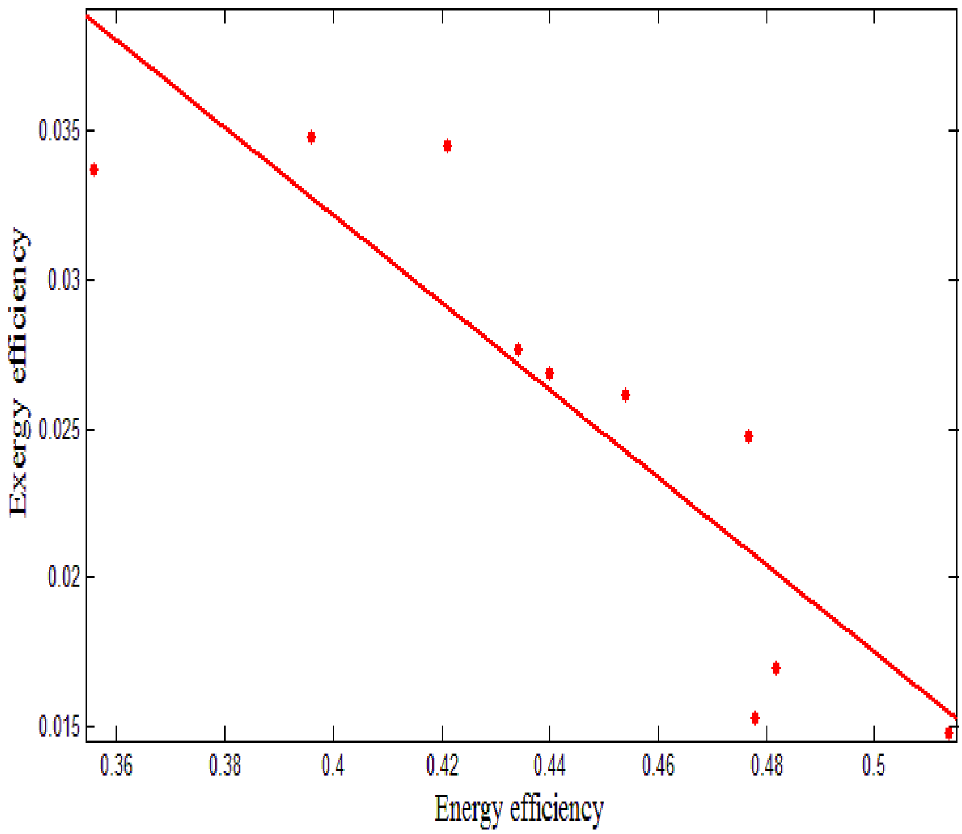


Figure 6.3 Exergy efficiency vs. energy efficiency for flat-plate collector

6.2 Evacuated-Tube Solar Collector Tables and Curves

Figure 6.4 shows the variation of evacuated-tube collector efficiency with ΔT/I.

Appendix D shows the table of results for evacuated-tube solar collector, which the curve was created from it.

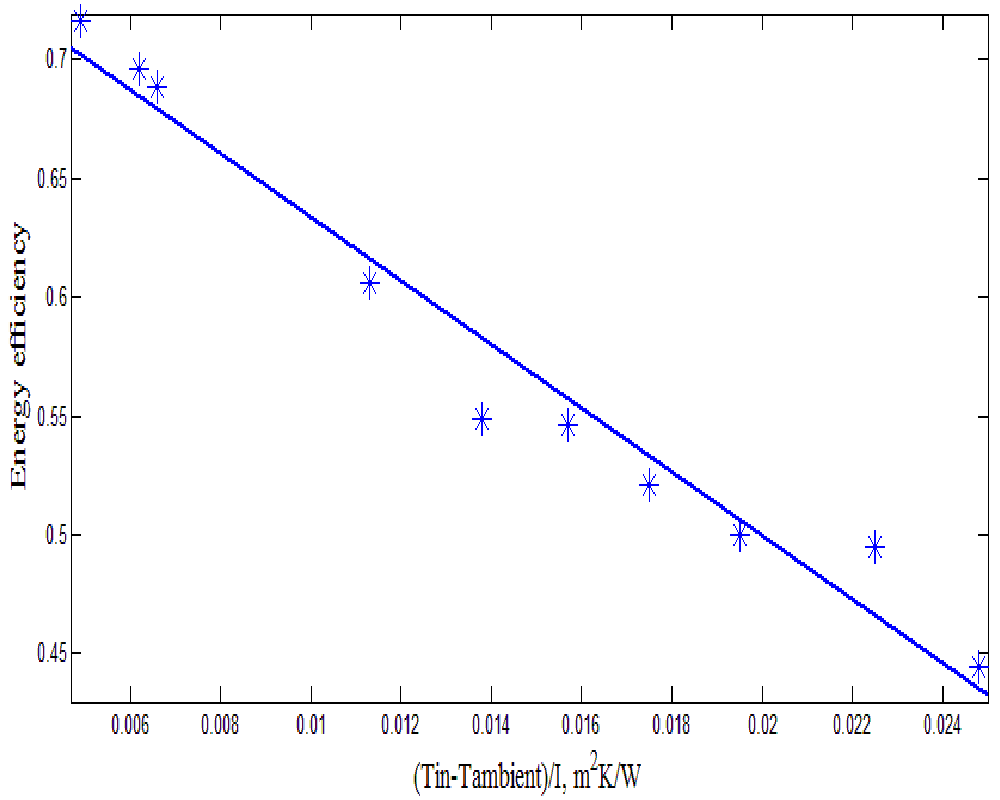


Figure 6.4 Energy efficiency for evacuated-tube collector (15/10-11/11)/2011

Fig. 6.5 shows the variation of the evacuated-tube collector efficiency with the inlet temperature.

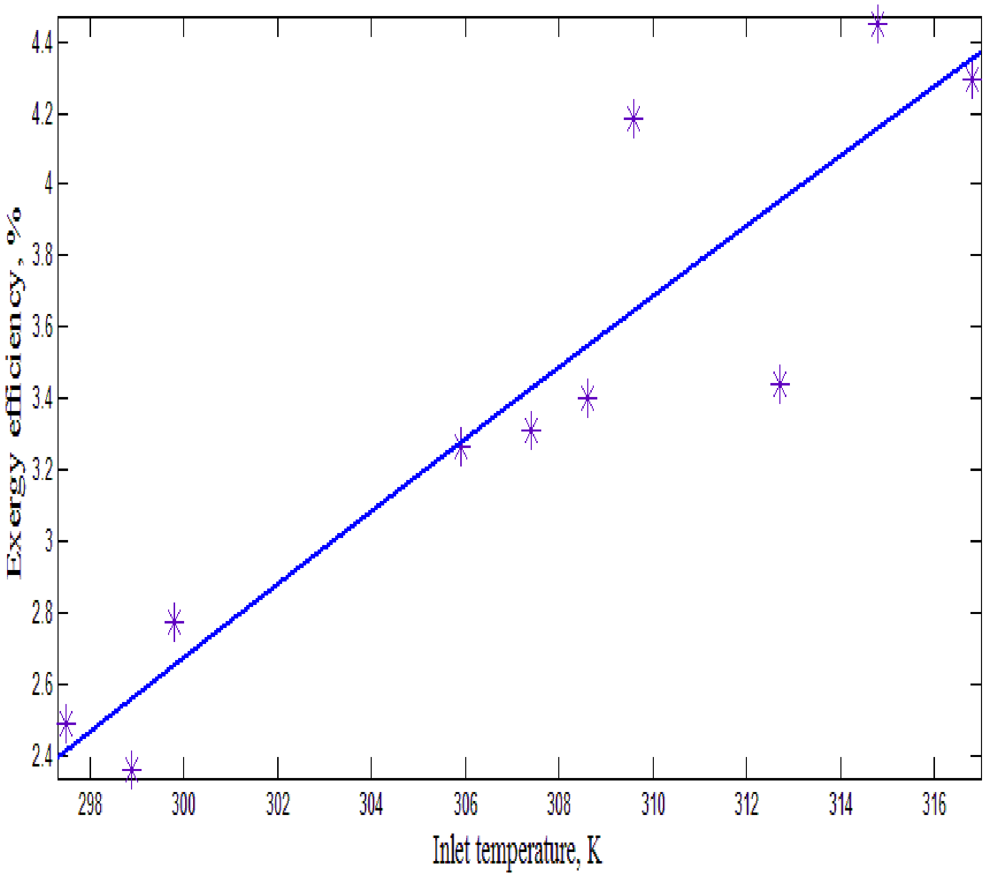


Figure 6.5 Exergy efficiency vs. inlet temperature for evacuated-tube collector

Fig. 6.6 shows the variation of the evacuated-tube collector exergy efficiency with the energy efficiency.

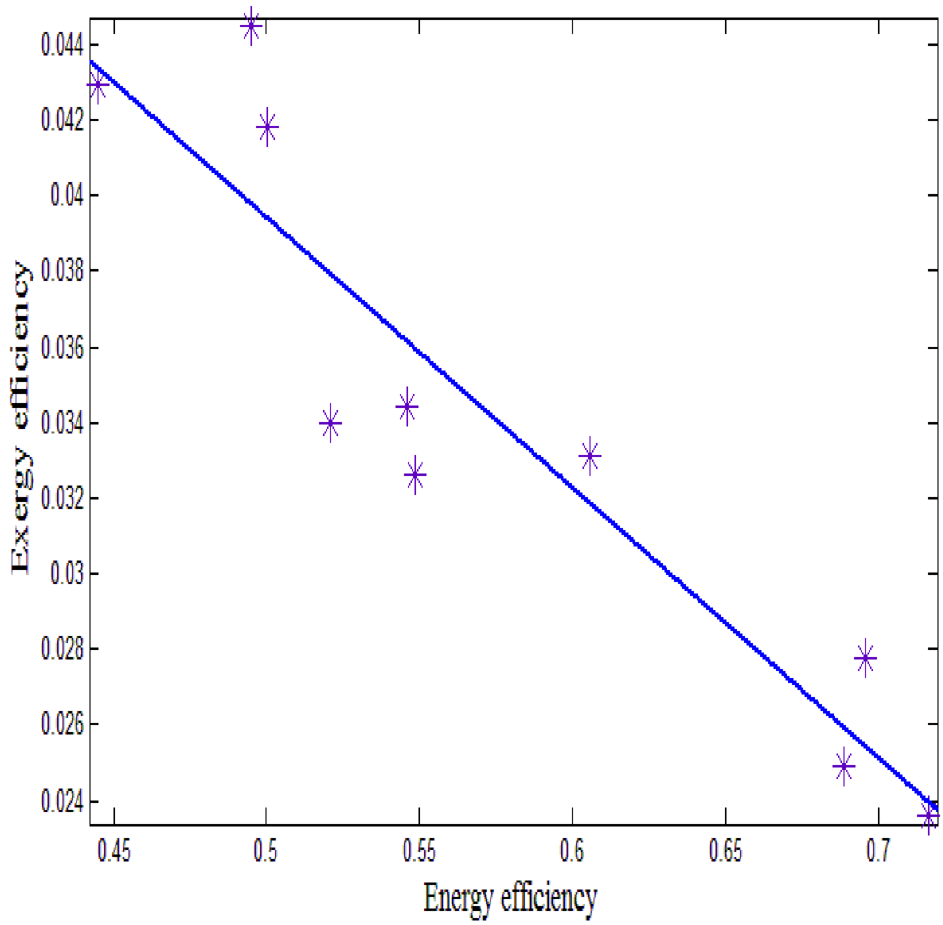


Figure 6.6 Exergy efficiency vs. energy efficiency for evacuated-tube collector

Chapter Seven: Discussion, Conclusion and Recommendations

7.1 Discussion

To understand the difference in performance between flat-plate and evacuated-tube solar collectors, the curves are grouped together, as follows.

7.1.1 Energy Efficiency vs. [ΔT/I].

Figure 7.1 shows in red the relation between the energy efficiency and [ΔT/I] for flat-plate solar collector, and in blue the relation between the energy efficiency and [ΔT/I] for evacuated-tube solar collector. ΔT here refers to the difference between the inlet temperature and the ambient temperature, The performance curves of both collectors are academic, where as [ΔT/I] increases the efficiency decreases for both collectors. Also the maximum efficiency of the evacuated-tube collector is typically higher than that of the flat-plate collector because the transmittance of the glass and the absorptance of the absorber are typically larger for the case of evacuated tube. However, as the value of ΔT becomes large, the energy efficiency for both collectors decreases because, at higher temperature of both collectors, the losses increase and the efficiency decrease. The efficiency of the evacuated tube collector decreases at a larger amount, as indicated by the higher slope of the curve than that of the flat-plate collector tube. This agrees well with typical results of evacuated-tube collector tests made at high values of solar radiation(Duffie and Beckman 2006). The value of the heat removal factor multiplied by the overall heat loss factor for flat-plate collector is (- 6.378), and for evacuated-tube collector is (-13.4). The resulted equations can be compared with the Hottel-Whillier equation for the useful heat gain (Q_u).

$$Q_u = A_p \times F_R[S - U_l(T_{in} - T_a)] \ldots\ldots\ldots\ldots\ldots\ldots 7.1$$

$$\eta_{en} = \frac{F_R \times S}{I} - (F_R \times U_l) \times \frac{\Delta T}{I} \ldots\ldots\ldots\ldots\ldots\ldots 7.2$$

Energy efficiency equations for the collectors were as follows:

For the flat-plate collector:

$$\eta_{en} = 0.5363 - 6.378 \times \frac{\Delta T}{I} \ldots\ldots\ldots\ldots\ldots\ldots 7.3$$

For the evacuated-tube collector:

$$\eta_{en} = 0.7676 - 13.4 \times \frac{\Delta T}{I} \ldots\ldots\ldots\ldots\ldots\ldots 7.4$$

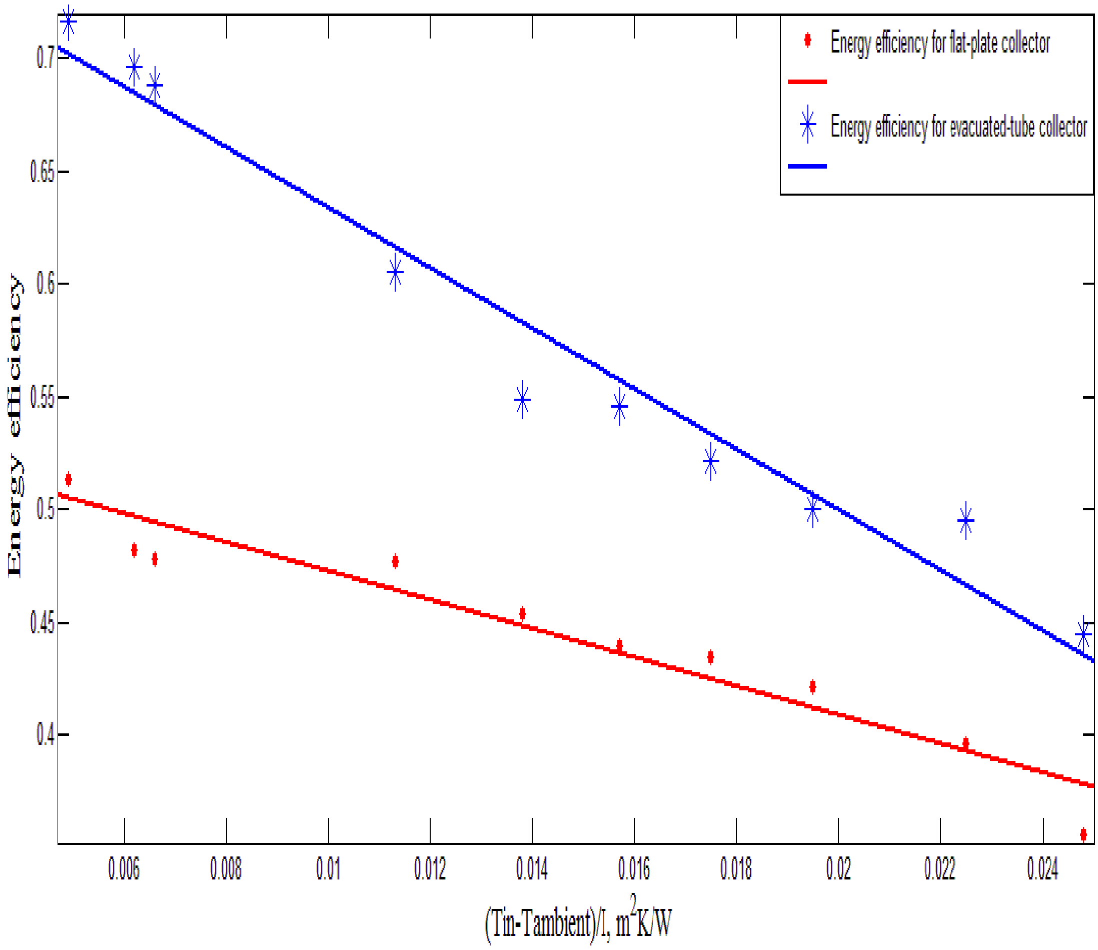


Figure 7.1 Comparison between flat-plate & evacuated-tube collectors in energy efficiency vs. (Tin-Tamb.)/I

7.1.2 Exergy Efficiency vs. Inlet Temperature.

The equation that describes the exergy efficiency behavior of the two solar collectors is the same. In general, the exergy efficiency increases as the inlet temperature increases for both collectors, as shown in Figure 7.2. The effect of inlet temperature on exergy efficiency for flat-plate collector is sharper than that for evacuated-tube collector. At a certain point the increase for the evacuated tube exergy efficiency becomes even less sharper and probably flattens at higher inlet temperatures. Those temperatures were not reached during testing. A comparison was made, however, with

similar results obtained by Farahat(2007) provided here as Figure 7.3 shows that the flattening trend is correct. This Figure shows also that the exergetic efficiency even decreases at higher inlet temperatures. The value of inlet temperature is larger than the values of ambient temperature, and this decreases the effect of those values on the relation between exergy efficiency and inlet temperature, according to equation 3.8.

The exergy efficiency vs. inlet temperature equations for the collectors were as follows:

For the flat-plate collector:

$$\eta_{Ex} = 2.018 \times T_{in} - 0.003117 \times {T_{in}}^2 - 323.1 \quad \dots \quad \dots \dots \dots ..7.5$$

And for the evacuated-tube collector:

$$\eta_{Ex} = 0.2293 \times T_{in} - 0.00021 \times {T_{in}}^2 - 47.21 \quad \dots \dots \dots \dots ..7.6$$

The most important result of this work is that, as shown in Fig. 7.2, the exergy efficiency of the evacuated-tube collector is larger than that of the flat-plate collector.

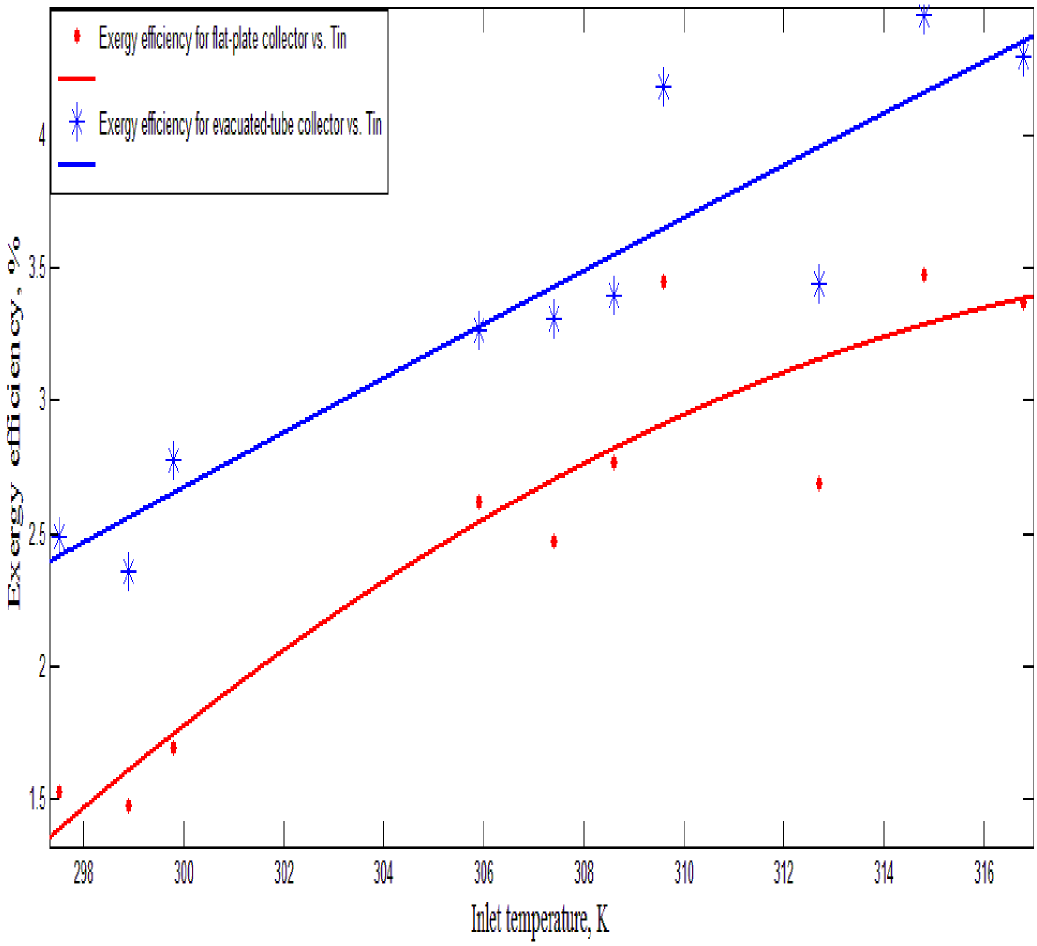


Figure 7.2 Comparison between flat-plate & evacuated-tube collectors in exergy efficiency vs inlet temperature

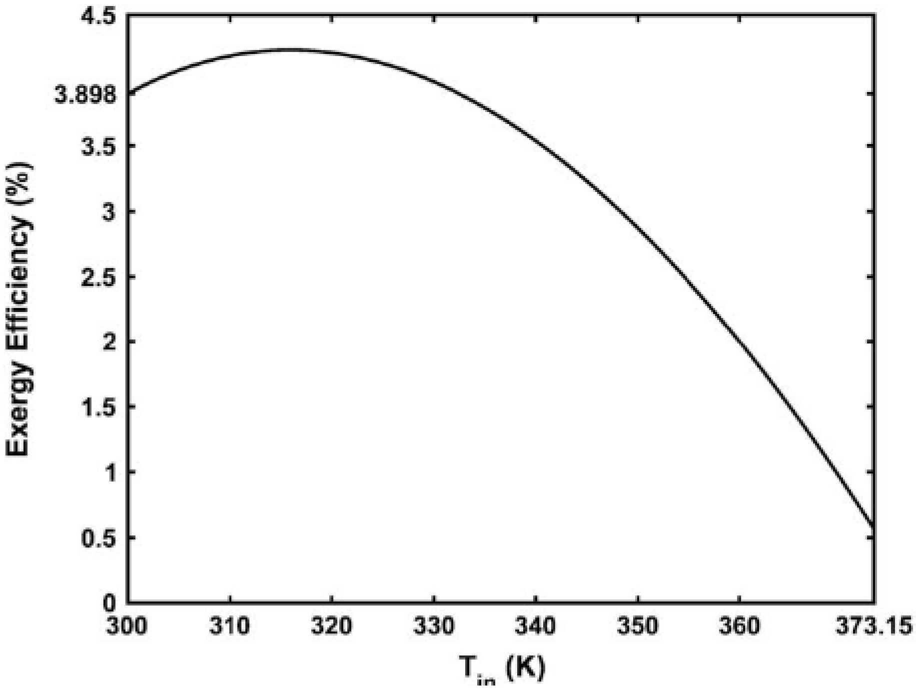


Figure 7.3 Variation of the exergy efficiency vs. inlet temperature [Farahat].

7.2 Conclusions

From all comparisons established in the discussion, the conclusions are:

- The energy and exergy efficiency of evacuated-tube collector is generally larger than that of flat-plate collector.
- The amount of energy losses in evacuated-tube collector are more than that for flat-plate collector for high ambient temperatures and high radiation intensities.
- The variables that are calculated in this study (incident solar energy, ambient temperature, and inlet temperature) have larger effects on the flat-plate collector than evacuated-tube collector.

7.3 Recommendations

- The effects of each variable on the exergy efficiency of flat-plate and evacuated-tube solar collectors must be studied alone.
- The results of energy and exergy efficiencies for flat-plate and evacuated-tube collectors in this study may make obvious vision to select the better solar collector according to the case for users.
- Please do not compare values of figure 6.2 with figure 6.3 or values of figure 6.4 with figure 6.6, because of different other parameters

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Appendix A: Thermoelectric Voltages in Millivolts

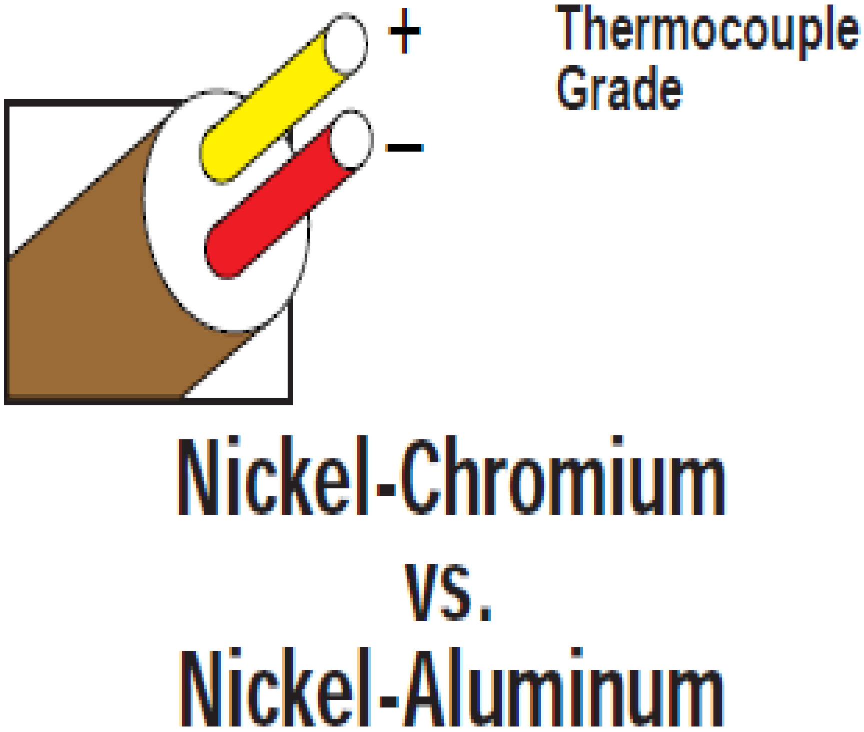


Table A.1: Thermoelectric voltage in millivolts.

°C	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	°C
-260	-6.458	-6.457	-6.456	-6.455	-6.453	-6.452	-6.450	-6.448	-6.446	-6.444	-6.441	-260
-250	-6.441	-6.438	-6.435	-6.432	-6.429	-6.425	-6.421	-6.417	-6.413	-6.408	-6.404	-250
-240	-6.404	-6.399	-6.393	-6.388	-6.382	-6.377	-6.370	-6.364	-6.358	-6.351	-6.344	-240
-230	-6.344	-6.337	-6.329	-6.322	-6.314	-6.306	-6.297	-6.289	-6.280	-6.271	-6.262	-230
-220	-6.262	-6.252	-6.243	-6.233	-6.223	-6.213	-6.202	-6.192	-6.181	-6.170	-6.158	-220
-210	-6.158	-6.147	-6.135	-6.123	-6.111	-6.099	-6.087	-6.074	-6.061	-6.048	-6.035	-210
-200	-6.035	-6.021	-6.007	-5.994	-5.980	-5.965	-5.951	-5.936	-5.922	-5.907	-5.891	-200
-190	-5.891	-5.876	-5.861	-5.845	-5.829	-5.813	-5.797	-5.780	-5.763	-5.747	-5.730	-190
-180	-5.730	-5.713	-5.695	-5.678	-5.660	-5.642	-5.624	-5.606	-5.588	-5.569	-5.550	-180
-170	-5.550	-5.531	-5.512	-5.493	-5.474	-5.454	-5.435	-5.415	-5.395	-5.374	-5.354	-170
-160	-5.354	-5.333	-5.313	-5.292	-5.271	-5.250	-5.228	-5.207	-5.185	-5.163	-5.141	-160
-150	-5.141	-5.119	-5.097	-5.074	-5.052	-5.029	-5.006	-4.983	-4.960	-4.936	-4.913	-150
-140	-4.913	-4.889	-4.865	-4.841	-4.817	-4.793	-4.768	-4.744	-4.719	-4.694	-4.669	-140
-130	-4.669	-4.644	-4.618	-4.593	-4.567	-4.542	-4.516	-4.490	-4.463	-4.437	-4.411	-130
-120	-4.411	-4.384	-4.357	-4.330	-4.303	-4.276	-4.249	-4.221	-4.194	-4.166	-4.138	-120
-110	-4.138	-4.110	-4.082	-4.054	-4.025	-3.997	-3.968	-3.939	-3.911	-3.882	-3.852	-110
-100	-3.852	-3.823	-3.794	-3.764	-3.734	-3.705	-3.675	-3.645	-3.614	-3.584	-3.554	-100
-90	-3.554	-3.523	-3.492	-3.462	-3.431	-3.400	-3.368	-3.337	-3.306	-3.274	-3.243	-90
-80	-3.243	-3.211	-3.179	-3.147	-3.115	-3.083	-3.050	-3.018	-2.986	-2.953	-2.920	-80
-70	-2.920	-2.887	-2.854	-2.821	-2.788	-2.755	-2.721	-2.688	-2.654	-2.620	-2.587	-70
-60	-2.587	-2.553	-2.519	-2.485	-2.450	-2.416	-2.382	-2.347	-2.312	-2.278	-2.243	-60
-50	-2.243	-2.208	-2.173	-2.138	-2.103	-2.067	-2.032	-1.996	-1.961	-1.925	-1.889	-50
-40	-1.889	-1.854	-1.818	-1.782	-1.745	-1.709	-1.673	-1.637	-1.600	-1.564	-1.527	-40
-30	-1.527	-1.490	-1.453	-1.417	-1.380	-1.343	-1.305	-1.268	-1.231	-1.194	-1.156	-30
-20	-1.156	-1.119	-1.081	-1.043	-1.006	-0.968	-0.930	-0.892	-0.854	-0.816	-0.778	-20
-10	-0.778	-0.739	-0.701	-0.663	-0.624	-0.586	-0.547	-0.508	-0.470	-0.431	-0.392	-10
0	-0.392	-0.353	-0.314	-0.275	-0.236	-0.197	-0.157	-0.118	-0.079	-0.039	0.000	0

0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436	50
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851	60
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267	70
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682	80
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096	90
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509	100
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920	110
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328	120
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735	130
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138	140
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540	150
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941	160
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340	170
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739	180
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138	190
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539	200
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940	210
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343	220
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747	230
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153	240
°C	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**°C**

°C	0	1	2	3	4	5	6	7	8	9	10	°C
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520	10.561	250
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930	10.971	260
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341	11.382	270
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753	11.795	280
290	11.795	11.836	11.877	11.919	11.960	12.001	12.043	12.084	12.126	12.167	12.209	290
300	12.209	12.250	12.291	12.333	12.374	12.416	12.457	12.499	12.540	12.582	12.624	300
310	12.624	12.665	12.707	12.748	12.790	12.831	12.873	12.915	12.956	12.998	13.040	310
320	13.040	13.081	13.123	13.165	13.206	13.248	13.290	13.331	13.373	13.415	13.457	320
330	13.457	13.498	13.540	13.582	13.624	13.665	13.707	13.749	13.791	13.833	13.874	330
340	13.874	13.916	13.958	14.000	14.042	14.084	14.126	14.167	14.209	14.251	14.293	340
350	14.293	14.335	14.377	14.419	14.461	14.503	14.545	14.587	14.629	14.671	14.713	350
360	14.713	14.755	14.797	14.839	14.881	14.923	14.965	15.007	15.049	15.091	15.133	360
370	15.133	15.175	15.217	15.259	15.301	15.343	15.385	15.427	15.469	15.511	15.554	370
380	15.554	15.596	15.638	15.680	15.722	15.764	15.806	15.849	15.891	15.933	15.975	380
390	15.975	16.017	16.059	16.102	16.144	16.186	16.228	16.270	16.313	16.355	16.397	390
400	16.397	16.439	16.482	16.524	16.566	16.608	16.651	16.693	16.735	16.778	16.820	400
410	16.820	16.862	16.904	16.947	16.989	17.031	17.074	17.116	17.158	17.201	17.243	410
420	17.243	17.285	17.328	17.370	17.413	17.455	17.497	17.540	17.582	17.624	17.667	420
430	17.667	17.709	17.752	17.794	17.837	17.879	17.921	17.964	18.006	18.049	18.091	430
440	18.091	18.134	18.176	18.218	18.261	18.303	18.346	18.388	18.431	18.473	18.516	440
450	18.516	18.558	18.601	18.643	18.686	18.728	18.771	18.813	18.856	18.898	18.941	450
460	18.941	18.983	19.026	19.068	19.111	19.154	19.196	19.239	19.281	19.324	19.366	460
470	19.366	19.409	19.451	19.494	19.537	19.579	19.622	19.664	19.707	19.750	19.792	470
480	19.792	19.835	19.877	19.920	19.962	20.005	20.048	20.090	20.133	20.175	20.218	480
490	20.218	20.261	20.303	20.346	20.389	20.431	20.474	20.516	20.559	20.602	20.644	490
500	20.644	20.687	20.730	20.772	20.815	20.857	20.900	20.943	20.985	21.028	21.071	500
510	21.071	21.113	21.156	21.199	21.241	21.284	21.326	21.369	21.412	21.454	21.497	510
520	21.497	21.540	21.582	21.625	21.668	21.710	21.753	21.796	21.838	21.881	21.924	520
530	21.924	21.966	22.009	22.052	22.094	22.137	22.179	22.222	22.265	22.307	22.350	530
540	22.350	22.393	22.435	22.478	22.521	22.563	22.606	22.649	22.691	22.734	22.776	540

550	22.776	22.819	22.862	22.904	22.947	22.990	23.032	23.075	23.117	23.160	23.203	550
560	23.203	23.245	23.288	23.331	23.373	23.416	23.458	23.501	23.544	23.586	23.629	560
570	23.629	23.671	23.714	23.757	23.799	23.842	23.884	23.927	23.970	24.012	24.055	570
580	24.055	24.097	24.140	24.182	24.225	24.267	24.310	24.353	24.395	24.438	24.480	580
590	24.480	24.523	24.565	24.608	24.650	24.693	24.735	24.778	24.820	24.863	24.905	590
600	24.905	24.948	24.990	25.033	25.075	25.118	25.160	25.203	25.245	25.288	25.330	600
610	25.330	25.373	25.415	25.458	25.500	25.543	25.585	25.627	25.670	25.712	25.755	610
620	25.755	25.797	25.840	25.882	25.924	25.967	26.009	26.052	26.094	26.136	26.179	620
630	26.179	26.221	26.263	26.306	26.348	26.390	26.433	26.475	26.517	26.560	26.602	630
640	26.602	26.644	26.687	26.729	26.771	26.814	26.856	26.898	26.940	26.983	27.025	640
650	27.025	27.067	27.109	27.152	27.194	27.236	27.278	27.320	27.363	27.405	27.447	650
660	27.447	27.489	27.531	27.574	27.616	27.658	27.700	27.742	27.784	27.826	27.869	660
670	27.869	27.911	27.953	27.995	28.037	28.079	28.121	28.163	28.205	28.247	28.289	670
680	28.289	28.332	28.374	28.416	28.458	28.500	28.542	28.584	28.626	28.668	28.710	680
690	28.710	28.752	28.794	28.835	28.877	28.919	28.961	29.003	29.045	29.087	29.129	690
700	29.129	29.171	29.213	29.255	29.297	29.338	29.380	29.422	29.464	29.506	29.548	700
710	29.548	29.589	29.631	29.673	29.715	29.757	29.798	29.840	29.882	29.924	29.965	710
720	29.965	30.007	30.049	30.090	30.132	30.174	30.216	30.257	30.299	30.341	30.382	720
730	30.382	30.424	30.466	30.507	30.549	30.590	30.632	30.674	30.715	30.757	30.798	730
740	30.798	30.840	30.881	30.923	30.964	31.006	31.047	31.089	31.130	31.172	31.213	740
750	31.213	31.255	31.296	31.338	31.379	31.421	31.462	31.504	31.545	31.586	31.628	750
760	31.628	31.669	31.710	31.752	31.793	31.834	31.876	31.917	31.958	32.000	32.041	760
770	32.041	32.082	32.124	32.165	32.206	32.247	32.289	32.330	32.371	32.412	32.453	770
780	32.453	32.495	32.536	32.577	32.618	32.659	32.700	32.742	32.783	32.824	32.865	780
790	32.865	32.906	32.947	32.988	33.029	33.070	33.111	33.152	33.193	33.234	33.275	790
°C	0	1	2	3	4	5	6	7	8	9	10	°C

Appendix B: Data acquisition card specifications

Table B.1: Data acquisition card specifications.

Specifications

Data Acquisition	Data Acquisition Card
Form Factor	PC Board
Data Acquisition Specifications	
Analog Channels	4
Differential Channels	Yes
Digital I/O Channels	0
Sampling Frequency	0.0120 kHz
Resolution	24 bits
Input Specifications	
DC Voltage	+/-80V
Inputs	Thermocouple Input
User Interface	Computer Programmable
Host Connection	USB
Application	General Lab & Industrial; Environmental; Vehicular
Software	
Name	LabView et al.

Appendix C: Flat-plate solar collector tables

Table C.1: Energy and exergy efficiency results for flat-plate solar collector.

Date	$T_{Ambient}$ $[K]$	T_{in} $[K]$	T_{out} $[K]$	I $[W/m^2]$	Energy Efficiency %	ΔT/I	Exergy Efficiency%
15/10	293	308.6	313.37	920	0.4341	0.0175	2.7655529
16/10	295	307.4	313.48	1067	0.4766	0.0113	2.475014
21/10	292	305.9	311.32	1005	0.454	0.0138	2.6157126
24/10	297	312.7	317.82	979	0.4399	0.0157	2.6865006
31/10	291	314.8	319.75	1057	0.396	0.0225	3.4780448
1/11	291	316.8	321.25	1059	0.3558	0.0248	3.3692671
7/11	288	309.6	315.05	1093	0.4211	0.0195	3.4486034
9/11	293	299.8	306.1	1095	0.4817	0.0062	1.6940534
10/11	291	297.5	302.98	968	0.478	0.0066	1.5288733
11/11	294	298.9	305.15	1019	0.5137	0.0049	1.4755765

Appendix D: Evacuated-tube solar collector tables

Table D.1: Energy and exergy efficiency results for evacuated-tube solar collector.

Date	$T_{Ambient}$ $[K]$	T_{in} $[K]$	T_{out} $[K]$	I $[W/m^2]$	Energy Efficiency %	ΔT/I	Exergy Efficiency%
15/10	293	308.6	314.328	920	0.5211	0.0175	3.399998
16/10	295	307.4	315.125	1067	0.6058	0.0113	3.3100171
21/10	292	305.9	312.457	1005	0.5487	0.0138	3.2631687
24/10	297	312.7	319.055	979	0.5459	0.0157	3.441632
31/10	291	314.8	321	1057	0.4949	0.0225	4.4506677
1/11	291	316.8	322.375	1059	0.4448	0.0248	4.2963305
7/11	288	309.6	316.083	1093	0.5003	0.0195	4.1829711
9/11	293	299.8	308.9	1095	0.6958	0.0062	2.776025
10/11	291	297.5	305.417	968	0.6884	0.0066	2.4924397
11/11	294	298.9	307.617	1019	0.7164	0.0049	2.3593865

Appendix E: Uncertainty analysis

The method used for estimating uncertainty in experimental results has been presented by Kline and Mc Clintock. The method is based on careful specification of uncertainties in the various primary experimental measurements.

The uncertainty of each device is taken as one-half the smallest scale interval reading and its recorded in the table below:

Table E.1: The Uncertainty of the measurement devices.

Measuring Device	Uncertainty
Metric Scale	± 0.005 m
Temperature Processor (Thermocouples)	± 0.05°C
Radiation Processor (Pyranometer)	± 0.5 W/m^2
Graduating Cylinder	± 1 mm

The analysis was made using results obtained on november, 1st for flat-plate collector and evacuated-tube collector which gave the following readings:

$I = 1059\ W/m^2$

$T_{in} = 316.8\ K$

$T_{ambient} = 291K$

$T_{out,\ F.P.C.} = 321.25K$

$\dot{m}_{F.P.C.} = 27$ ml/sec.

$\eta_{exergy,\ F.P.C.} = 3.36926\%$

$\eta_{exergy,\ E.T.C.} = 4.29633\%$

$T_{out,\ E.T.C.} = 322.375$

$\dot{m}_{E.T.C.} = 41$ ml/sec.

From these readings, the uncertainty of the still hourly efficiency can be found from equation 3.8;

$$\eta_{ex} = \frac{\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{IA_p\left(1 - \frac{T_a}{T_s}\right)}$$

The uncertainty in exergy efficiency can found as follows:

A. Flat-Plate Collector:

- Uncertainty in Area:

$$A_P = L \times W$$

Where:

A_P: Plate Area.

L: Plate Length.

W: Plate Width.

Thus,

$L = L \pm \omega_L$=1.74± 0.005 m

$W = W \pm \omega_W$ = 0.77 ± 0.005 m

$$\omega_{A_P} = \pm\sqrt{\left(\left(\frac{\partial A_p}{\partial L}\right)\omega_L\right)^2 + \left(\left(\frac{\partial A_P}{\partial W}\right)\omega_W\right)^2}$$

$$\omega_{A_P} = \pm\sqrt{(W \times \omega_L)^2 + (L \times \omega_W)^2}$$

Substituting the values, then:

$$\omega_{A_P} = \pm\sqrt{(0.77 \times 0.005)^2 + (1.74 \times 0.005)^2}$$

$$\omega_{A_P} = \pm 0.00951\ m^2$$

- Uncertainty in Exergy Efficiency:

$$\eta_{ex} = \frac{\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times A_p\left(1 - \frac{T_a}{T_s}\right)}$$

Where:

$I = 1059 \pm 0.5\ W/m^2$.

$\dot{m} = 27 \pm 1$ mL/sec.

$A_P = 1.34 \pm 0.00951\ m^2$

Uncertainty in exergy efficiency is:

$$\eta_{Exergy} = \pm\sqrt{\left(\left(\frac{\partial\eta}{\partial\dot{m}}\right)\omega_{\dot{m}}\right)^2 + \left(\left(\frac{\partial\eta}{\partial A_P}\right)\omega_{A_P}\right)^2 + \left(\left(\frac{\partial\eta}{\partial I}\right)\omega_I\right)^2 + \left(\left(\frac{\partial\eta}{\partial T_{in}}\right)\omega_{T_{in}}\right)^2 + \left(\left(\frac{\partial\eta}{\partial T_{out}}\right)\omega_{T_{out}}\right)^2 + \left(\left(\frac{\partial\eta}{\partial T_{ambient}}\right)\omega_{T_{ambient}}\right)^2}$$

Where:

$$\frac{\partial\eta}{\partial\dot{m}} = \frac{\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times A_p\left(1 - \frac{T_a}{T_s}\right)}$$

$$\frac{\partial\eta}{\partial \mathrm{A_P}} = \frac{-\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times \left(1 - \frac{T_a}{T_s}\right) \times {A_p}^2}$$

$$\frac{\partial\eta}{\partial \mathrm{I}} = \frac{-\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{A_p \times \left(1 - \frac{T_a}{T_s}\right) \times I^2}$$

$$\frac{\partial\eta}{\partial \mathrm{T_{in}}} = \frac{-\dot{m}\left[C_p\left(1 - \left(\frac{T_a}{T_{in}}\right)\right)\right]}{I \times A_p \times \left(1 - \frac{T_a}{T_s}\right)}$$

$$\frac{\partial\eta}{\partial \mathrm{T_{out}}} = \frac{\dot{m}\left[C_p\left(1 - \left(\frac{T_a}{T_{out}}\right)\right)\right]}{I \times A_p \times \left(1 - \frac{T_a}{T_s}\right)}$$

$$\frac{\partial\eta}{\partial \mathrm{T_a}} = -\frac{\dot{m} \times C_p \times T_s\left[\left(T_{out} - T_{in} - T_s \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times A_p \times (T_s - T_a)^2}$$

Then

$$\eta_{\mathrm{exergy}} = \pm\sqrt{\begin{array}{c}(1.23530073 \times 10^{-3})^2 + (-2.367075883 \times 10^{-4})^2 + \\ (-1.574745973 \times 10^{-5})^2 + (-3.47482719 \times 10^{-4})^2 + \\ (4.017731599 \times 10^{-4})^2 + (-5.916614352 \times 10^{-5})^2\end{array}}$$

$$\eta_{\mathrm{exergy}} = \pm\sqrt{1.867905806 \times 10^{-6}} = \pm 0.001366 = \pm 0.1366\%$$

Thus the exergy efficiency is $\eta_{\mathrm{exergy}} = 3.36926\% \pm 0.1366\%$

B. Evacuated-Tube Collector:

- Uncertainty in Area:

$$\mathrm{A_E} = \mathrm{L} \times \mathrm{D} \times \text{Pipes Number}$$

Where:

$\mathrm{A_E}$: Evacuated tubes Area.

L: Pipe Length.

D: Pipe Diameter.

Pipes Number: 20 pipe.

Thus,

$\mathrm{L} = \mathrm{L} \pm \omega_{\mathrm{L}} = 1.8 \pm 0.005$ m

$\mathrm{D} = \mathrm{D} \pm \omega_{\mathrm{D}} = 0.057 \pm 0.005$ m

$$\omega_{\mathrm{AE}} = \pm \sqrt{\left(\left(\frac{\partial A_E}{\partial L}\right)\omega_{\mathrm{L}}\right)^2 + \left(\left(\frac{\partial A_E}{\partial D}\right)\omega_{\mathrm{D}}\right)^2}$$

$$\omega_{\mathrm{AE}} = \pm \sqrt{(D \times \omega_{\mathrm{L}})^2 + (L \times \omega_{\mathrm{D}})^2}$$

Substituting the values, then:

$$\omega_{\mathrm{AE}} = \pm \sqrt{(0.057 \times 0.005)^2 + (1.8 \times 0.005)^2}$$

$$\omega_{\mathrm{AE}} = \pm 0.009004\ m^2$$

- Uncertainty in Exergy Efficiency:

$$\eta_{ex} = \frac{\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times \mathrm{A_E}\left(1 - \frac{T_a}{T_s}\right)}$$

Where:

I = 1059 ± 0.5 W/m^2.

ṁ = 41 ± 1 mL/sec.

$\mathrm{A_E}$ = 2.052± 0.009004 m^2

Uncertainty in exergy efficiency is:

$$\eta_{\mathrm{Exergy}} = \pm\sqrt{\left(\left(\frac{\partial\eta}{\partial\dot{\mathrm{m}}}\right)\omega_{\dot{\mathrm{m}}}\right)^2 + \left(\left(\frac{\partial\eta}{\partial\mathrm{A_E}}\right)\omega_{\mathrm{A_E}}\right)^2 + \left(\left(\frac{\partial\eta}{\partial\mathrm{I}}\right)\omega_{\mathrm{I}}\right)^2 + \left(\left(\frac{\partial\eta}{\partial\mathrm{T_{in}}}\right)\omega_{\mathrm{T_{in}}}\right)^2 + \left(\left(\frac{\partial\eta}{\partial\mathrm{T_{out}}}\right)\omega_{\mathrm{T_{out}}}\right)^2 + \left(\left(\frac{\partial\eta}{\partial\mathrm{T_{ambient}}}\right)\omega_{\mathrm{T_{ambient}}}\right)^2}$$

Where:

$$\frac{\partial\eta}{\partial\dot{\mathrm{m}}} = \frac{\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times A_E\left(1 - \frac{T_a}{T_s}\right)}$$

$$\frac{\partial\eta}{\partial\mathrm{A_E}} = \frac{-\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times \left(1 - \frac{T_a}{T_s}\right) \times \mathrm{A_E}^{\,2}}$$

$$\frac{\partial\eta}{\partial \mathrm{I}} = \frac{-\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{A_E \times \left(1 - \frac{T_a}{T_s}\right) \times I^2}$$

$$\frac{\partial\eta}{\partial \mathrm{T_{in}}} = \frac{-\dot{m}\left[C_p\left(1 - \left(\frac{T_a}{T_{in}}\right)\right)\right]}{I \times A_E \times \left(1 - \frac{T_a}{T_s}\right)}$$

$$\frac{\partial\eta}{\partial \mathrm{T_{out}}} = \frac{\dot{m}\left[C_p\left(1 - \left(\frac{T_a}{T_{out}}\right)\right)\right]}{I \times A_E \times \left(1 - \frac{T_a}{T_s}\right)}$$

$$\frac{\partial\eta}{\partial \mathrm{T_a}} = -\frac{\dot{m} \times C_p \times T_s\left[\left(T_{out} - T_{in} - T_s \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times A_E \times (T_s - T_a)^2}$$

Then

$$\eta_{\mathrm{exergy}} = \pm\sqrt{\begin{gathered}(1.028990795 \times 10^{-3})^2 + (-1.851200574 \times 10^{-4})^2 + \\ (-1.991908527 \times 10^{-5})^2 + (-3.445726044 \times 10^{-4})^2 + \\ (4.117831692 \times 10^{-4})^2 + (-7.328981619 \times 10^{-5})^2\end{gathered}}$$

$$\eta_{\mathrm{exergy}} = \pm\sqrt{1.387155317 \times 10^{-6}} = \pm 0.00117777 = \pm 0.117777\%$$

Thus the exergy efficiency is $\eta_{\mathrm{exergy}} = 4.29633\% \pm 0.117777\%$

Appendix F: Sample of calculations

The readings of inlet, outlet, ambient temperatures, mass flow rate, and incident solar energy, are necessary variables needed to determine the values of energy and exergy efficiencies for flat-plate and evacuated-tube collectors. In this appendix, sample of calculation is introduced to explain that, using results obtained on november, 1st for flat-plate collector and evacuated-tube collector which gave the following readings:

$I = 1059\ W/m^2$

$T_{in} = 316.8\ K$

$T_{ambient} = 291K$

$T_{out,\ F.P.C.} = 321.25K$

$T_{out,\ E.T.C.} = 322.375K$

$\dot{m}_{F.P.C.} = 27$ ml/sec.

$\dot{m}_{E.T.C.} = 41$ ml/sec.

$\eta_{exergy,\ F.P.C.} = 3.36926\%$

$\eta_{exergy,\ E.T.C.} = 4.29633\%$

.

a. Flat-plate collector calculations:

1. thermal perfomance(energy efficiency)

$$\eta_{en} = \frac{\dot{m}C_p(T_{out} - T_{in})}{I_T A_p}$$

$$\eta_{en} = \frac{0.02 \times 1.34 \times 4185 \times (321.25 - 316.8)}{1059 \times 1.34}$$

$$\eta_{en} = 0.3558$$

$$\eta_{en} = 35.58\%$$

2. Exergy efficiency

$$\eta_{ex} = \frac{\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times A_p\left(1 - \frac{T_a}{T_s}\right)}$$

$$\eta_{ex} = \frac{0.02 \times 1.34 \times \left[4185\left(321.25 - 316.8 - 291 \times \ln\left(\frac{321.25}{316.8}\right)\right)\right]}{1059 \times 1.34 \times \left(1 - \frac{291}{4350}\right)}$$

$$\eta_{ex} = \frac{0.02 \times [4185 \times (321.25 - 316.8 - 4.059152)]}{1059 \times (1 - 0.06689)}$$

$$\eta_{ex} = 3.3692\%$$

b. Evacuated-tube calculations:

1. thermal perfomance(energy efficiency)

$$\eta_{en} = \frac{\dot{m}C_p(T_{out} - T_{in})}{I_T A_p}$$

$$\eta_{en} = \frac{0.02 \times 2.052 \times 4185 \times (322.375 - 316.8)}{1059 \times 2.052}$$

$$\eta_{en} = 0.4448$$

$$\eta_{en} = 44.48\%$$

2. Exergy efficiency

$$\eta_{ex} = \frac{\dot{m}\left[C_p\left(T_{out} - T_{in} - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right)\right]}{I \times A_p\left(1 - \frac{T_a}{T_s}\right)}$$

$$\eta_{ex} = \frac{0.02 \times 2.052 \times \left[4185\left(322.375 - 316.8 - 291 \times \ln\left(\frac{322.375}{316.8}\right)\right)\right]}{1059 \times 2.052 \times \left(1 - \frac{291}{4350}\right)}$$

$$\eta_{ex} = \frac{0.02 \times [4185 \times (322.375 - 316.8 - 5.076438)]}{1059 \times (1 - 0.06689)}$$

$$\eta_{ex} = 4.29633\%$$

تحليل الطاقة المتوفرة و الأداء في اللواقط الشمسية ذات الأنابيب المفرغة مقارنة باللواقط ذات الصفيحة المستوية

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ملخص

في هذه الدراسة تم بناء وفحص لاقطين شمسيين، الأول من اللواقط الشمسية المسطحة والثاني من اللواقط الشمسية ذات الأنابيب المفرغة، والهدف من هذا هو دراسة الأداء الحراري وكفاءة الطاقة المتوافرة من كلا اللاقطين. استخدم في هذه الدراسة مصدر ماء واحد من خزان تزويد مياه وكذلك نفس أجهزة القياس مثل المزدوجات الحرارية، ونظام تجميع البيانات المحوسب، وجهاز قياس شدة الإشعاع الشمسي لكلا اللاقطين. تم أخذ القراءات لكلا اللاقطين على مدار عشرة أيام مابين الساعة الحادية عشرة والنصف ولغاية الساعة الثانية عشرة والنصف ظهرا بالتوقيت الشمسي. تم تدوين البيانات لكل لاقط في نفس الوقت لضمان الحصول على نتائج تتساوى فيها جميع الظروف الجوية ويمكن ذلك من إجراء مقارنة بين اللاقطين الشمسيين.

وقد وجد أن كفاءة الطاقة والطاقة المتوافرة للاقط الشمسي ذي الأنابيب المفرغة أعلى من تلك العائدة للاقط الشمسي المسطح. كما وجد أن ضياعات الطاقة في الأنابيب المفرغة كانت أكبر من تلك التي للاقط الشمسي المسطح خصوصا عندما تكون درجة الحرارة المحيطة عالية وفي حالة ارتفاع درجة حرارة الماء الداخل على اللاقط الشمسي.